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The development of a continuous return stratified flow water tunnel is described, and the major problems are discussed. The goal of this effort is to provide a facility for studying flows with important buoyancy effects occurring in undersea applications and, in many cases, also of importance in fundamental oceanographic problems. The capabilities of the UCSD stratified water tunnel are ideal for investigation of flows with both variable density and velocity profiles.

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FINAL REPORT

Contract No. N00014-76-c-0702

Period: February 1976 - February 1977

Principal Investigator: C. W. Van Atta

Title: Turbulence in Stratified Flow and Ocean Physics

I. Research Program Plan

The objective of our research has been to design and develop a continuous return stratified flow water tunnel suitable for both fundamental and applied studies of fluid mechanical phenomena with significant buoyancy effects. The fundamental studies planned are measurements of uniform density gradient, uniform velocity shear behind a turbulence generating grid. Particular attention will be paid to the buoyancy and momentum flux terms in the governing turbulent energy balance equations. Other measurements are to be made in various wake flows such as cylinders and axisymmetric bodies. Experiments with both fundamental and applied interest are to be performdd on the solitary wave field induced by protrusions extending below the water surface. This experiment is motivated by observations made in the stratified flow beneath keels in pack ice. Many interesting experiments are planned to study the interaction of the internal wave field and velocity shear.

The long-term objectives of our research has dictated breaking new ground in water tunnel design. Turbulence measurements required relatively long run times to permit meaningful statistical data to be gathered. Tow tanks are not well suited to high quality turbulence measurements of a quantitative nature (requiring use of measurement techniques such as hot-film anemometers and capacitance density sensors) because of the amount of time required to gather a sufficient number of ensembles. Since unlimited amounts of water are not ordinarily available necessitating the continuous return approach. This in turn requires careful control of the inlet velocity and density profiles so that the proper stationarity condition is achieved. An earlier tunnel design did not include adequate provisions for density profile control so a decision was made early in 1976 to modify the design to reach the objectives described herein. Unfortunately, this choice did not permit producing quick scientific results, however limited the results would have been. We strongly emphasize that high quality turbulence measurements in sheared stratified flows will not be made without a development similar to the one we present in this report.

II. Major Accomplishments

The status of the UCSD stratified water tunnel project up to November 1976 was included in the renewal proposal submitted to ARPA last year. The text of this proposal and one of the appendices is presented in the Appendix to this report. We shall review the progress that has been made since this time and present an overall judgment of the approach to the original design objectives.

The basic tunnel structure is complete and we have been able to operate the tunnel since December of 1976. Initial leak testing proceeded smoothly and the tunnel integrity has proven to be excellent. Adjustable outlet weirs were installed, and the tunnel has been operated for periods of 1-1/2 hours without difficulty. Hot-film velocity signals have proven to

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be vibration free, a great improvement over the old water tunnel design. A sensor traversing system consisting of a stepper motor and a streamlined probe holder has been completed giving 0.003 inch resolution over the entire 10 inch water depth. Float gages have been constructed to monitor the depth of water in the lower reservoir tanks and will provide the accurate flow information needed to adjust the outlet weirs to match any desired inlet valve settings. Preliminary velocity measurements show that the background turbulence intensity u'/U to be about 5 to 8% with no attempt at turbulence management via straws, screens, and foam. We anticipate no problem in reducing the turbulence level to well below 1% and possibly below a few tenths of a percent, suitable for laminar flow measurements. The turbulence management section is readily accessible and can be tailored to meet any particular experimental needs. We are about to begin a series of runs with stratification to determine the level of mixing in the tunnel with time. These measurements will include velocity and density profiles at several longitudinal stations in the test section. The measurements will be done at a number of density profiles and velocity shears in order to properly cover the operating range of the water tunnel. These measurements will provide the important necessarily empirical information needed to complete installation of the density control system. The microprocessor (a Motorola M6800) has been assembled and a digital acquisition front end has been developed suitable for monitoring the density at the inlet to the test section of the water tunnel. The density control will be accomplished by opening and closing solenoid valves mounted over the water tunnel outlet manifold to control the flow rate of fresh and salt water into the system. The structure and flow system for the fresh and salt water lines has been completed and only requires the results of the preliminary mixing experiments before being installed on the water tunnel.

The present water tunnel design has been made as large as possible consistent with space and building requirements. A blow-down tunnel design would eliminate some difficult control problems, but the amount of water and therefore space required for the test section and velocities our design is capable of attaining would not be possible in anything but the largest, probably industrial, facility. The use of constant head gravity driven flow has proven successful. This technique requires larger volumes of water in the system (a large fraction of the water must reside in the upper reservoir tank), but the elimination of the swirling flow downstream of pump driven systems is worth the extra water required. At present our system is limited to about 50 cm/sec in the test section (for any one layer), but this is a limitation of the pumping capacity and not a limitation of the pressure head or other tunnel parameters. There does not appear to be any lower flow limit as might be present in a pump driven system. The overflow lines from the upper reservoir tanks are able to drain the maximum flow rate the pumps can deliver. The choice of instrumentation, hot-film and conductivity sensors, is a conservative one. While some development work with the conductivity sensor has been deemed important, we believe that nonintrusive

techniques such as laser anemometry, are not appropriate for us at this time. We decided to concentrate our developmental efforts on the water tunnel facility itself as much as possible. Laser techniques may prove to be appropriate even in strongly stratified flows, although a demonstration of a high quality commercial laser anemometer system in our water tunnel did not appear to perform well because of the large index of refraction fluctuations.

III. Problems Encountered

No major problems have appeared with the present tunnel design. Current experience verifies that the water temperature does rise significantly as anticipated and discussed in the proposal included in the Appendix. Formation of bubbles on the hot-film sensor may still be a problem, but we will not know until the water tunnel has been operated in the stratified mode. The saturation point of air in water decreases as the salinity increases thus making hot-film velocity probes more subject to bubbling. Progress with the tunnel fabrication was good despite the limited technician time available to us (50% of a man-year). The remainder of the work which remains could be easily accommodated by a technician at the same level.

IV. Future Plans

While some investment in capital equipment and fabrication is still needed, the UCSD stratified water tunnel is ready for a number of scientifically important experiments. Despite the break in funding, work will continue on several of these problems as time permits. A number of facility test experiments must be accomplished before installation of the density control system, but useful experimentation is expected to begin by May 1977.

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APPENDIX

Text of renewal proposal -- UCSD 9451

C. W. Van Atta
Principal Investigator

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ABSTRACT

The contractor shall conduct experimental and theoretical studies of stratified turbulent flows. The goal of these studies is to simulate flows with important buoyancy effects occurring in undersea applications and, in many cases, also of importance in fundamental oceanographic problems. The experimental program for these studies shall include development and control of a continuously operating stratified water channel and instrumentation capable of measuring two components of velocity and density. Measurements will be made of the time and spatial behavior of turbulence in decay behind grids, the characteristics of momentum and salinity wakes behind axisymmetric bodies and cylinders, behind self-propelled bodies, and in flow fields with uniform velocity and density gradients. Particular emphasis will be given to the measurement of the buoyancy flux terms as well as other measurable terms in the governing turbulence energy balance equations. Detailed measurements of the near-field internal wave field around axisymmetric bodies will be made. The measurements will be compared with related experimental work and with theoretical models for mixing and wave propagation in stratified flows.

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RESEARCH PLAN

I. Summary

Experimental studies and resulting technical applications involving stratified turbulent shear flows and wave disturbances near bodies have been severely limited by conventional towing tank configurations. We are pursuing a unique alternative approach utilizing a continuously flowing closed return stratified system. The present main experimental facility (Fig. 1, p. 16) is a continuously operating 10 layer stratified water channel, 25 cm × 40 cm in cross section and 500 cm in length. Each of the 10 salinity stratified flow layers is supplied by a separate mixing tank and is gravity driven by a separate upper reservoir tank. By varying the flow valve opening and the salt concentrations in the supply tanks, various initial flow velocity and fluid density profiles can be generated to simulate desired stratified conditions. A smaller calibration flow channel is used for probe calibrations and instrumentation development. A number of new problems are associated with this innovation, and new ground must be broken in several areas, including suppression of background turbulence level and control of multilayer shear and density profiles in the large channel, and associated instrumentation. The potential benefits of this work to future studies of stratified flow problems are well worth the difficulties being faced in our necessarily pioneering and exploratory studies. It is very desirable that continuing support be available over a period of three to four years, as the problems are of a difficult nature. We are very limited in personnel (1 faculty member, one research engineer, and two students), and we need to be sure of a student's support throughout his thesis tenure in order to proceed efficiently.

II. Outline of Present Plans

1. Subject Description

The present work is directed toward laboratory measurements of turbulent shear flows that are strongly influenced by density stratification on the order of that found in the ocean. The interaction of turbulent shear and stratification and the generation of random internal wave fields are dominant in many processes of interest, e.g., in the wakes of undersea vehicles travelling in the thermocline, in thermocline mixing, formation of microstructure in the ocean and atmosphere, and in other environmentally important areas of applied technology. In contrast to the universal success of Monin-Obukhov similarity scaling as applied to stratified flow in the earth's atmospheric boundary layer, there has been comparatively little advance in general understanding of oceanic problems on the same level, which could be usefully applied to problems of current interest. Field experiments are much more difficult in the ocean, and to

date have always been severely limited in scope, so that all the parameters necessary for a complete analysis have never been simultaneously available. In the laboratory, conditions are better, but there is still a serious lack of developed instrumentation for measurements in liquids and a lack of suitable water tunnel facilities with adequate long term measurement capabilities. In particular, direct measurements in liquids of the vertical flux of density, a quantity of primary importance, have not been reported in the literature. Tow tanks are commonly used for laboratory measurements in stratified flows, but many important problems cannot be modelled in such facilities, e.g. the production of a flow with both uniform density and velocity shear gradients and sufficient data for statistical significance in wake flows is extremely difficult to obtain in towed experiments.

2. Objectives

2.1 Measurements in stratified flows

Grid flow: Measure the effects of varying stratification (stability) on the decay of the turbulent density and velocity fluctuations and the growth of Taylor microscales. Compare the limiting case of very weak stratification with the several experiments reported on passive scalars in air.

Wake flows and mixing layers: Examine the behavior of length scales, rms velocity and density fluctuations, correlations including Reynolds stress $\overline{u'w'}$ and buoyancy flux $\overline{\rho'w'}$. Eventually measurements are needed for all terms except pressure velocity correlations to obtain complete energy balances for turbulent velocity and density fluctuations. Examine the near-field generation of internal waves by the body and wake.

Uniform gradient shear flow (see Future Plans, Paragraph 4.): Measurements of the development of mean velocity and density profiles, velocity and density fluctuations, Reynolds stress and buoyancy flux are desired to see if steady state values are approached. Determine the influence of buoyancy on larger scales of turbulence and growth rate of Taylor microscales. Comparisons are to be made with growth rates of passive scalar fluctuations obtained in grid experiments and in other experiments in air with a linear mean temperature profile and nonstratified sheared turbulence.

An overview of current knowledge of turbulent buoyant flow has been given by Stuhmiller (1976). Some very basic experimental information is required to guide the development of numerical models on such important problems as the radiation of internal waves from axisymmetric bodies and the interaction of turbulence and the generation of internal wave fields by wakes. Measurements of turbulence characteristics in various flows will provide validation data for computer codes which are beginning to apply

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higher-order modelling techniques to stratified flows (see Gibson & Launder (1975)). The higher-order modelling appears to be both computationally feasible and necessary to adequately simulate complex turbulent flows. The crucial element required is direct experimental information to assit in defining suitable turbulence models. Certain realizability conditions apply (Schumann (1976)), but these techniques cannot be used to derive specific terms needed to model the appropriate diffusion, pressure, and transport terms and still remain simple enough so that the computer code is not overwhelmed by excessive detail.

2.2 Water tunnel facility

Develop a continuous flow stratified water tunnel capable of maintaining desired density and velocity profiles for sufficient time to make statistically meaningful turbulence measurements. The appendix contains a description of a simple mixing model needed to control the density profile.

2.3 Instrumentation

Develop a hot-film probe capable of measuring $\overline{\rho' w'}$ for measurement of buoyancy flux. Investigate the mixed sensitivity to velocity and density of the hot-film sensor.

3. Recent Progress

3.1 Water tunnel facility

3.1.1 Problems encountered in previous design

The old water tunnel is currently being modified to meet our present and future research goals in stratified shear flow turbulence studies as determined from our work during the past year. Several problems with the previous water tunnel dictated that changes be made to obtain the desired operating characteristics. The problems we encountered were severe bubbling of the hot-film velocity sensors, large intensity background turbulence levels, inadequate capability for controlling the density profile with time, and relatively low maximum mean velocities.

The bubbling of the hot-film sensors was an extremely serious problem which required us to check several possible causes. Ultimately a small test loop was constructed using sections of clear plexiglas pipe to permit

observation of the flow in several critical regions. One of the propeller pumps from the previous water tunnel was installed to simulate the conditions in the old water tunnel. Numerous experiments were performed with hot-films and visual observations made of the flow immediately downstream of the propeller. The test loop demonstrated the severe bubbling problem observed in the water tunnel, and it was apparent that the small high speed propeller was driving dissolved air out of solution and creating a sizeable stream of bubbles which could not be quickly redissolved into the water before arriving at the velocity sensors. These tests suggested that in order to run an open system (that is, the test section of the water tunnel having a free surface) a different method of moving the water had to be adopted. Our experience with our small calibration water tunnel which operates as a constant head overflow system supplied by a centrifugal pump suggested that we try this method on a large scale for the water tunnel itself. We have never had a bubbling problem on the hot-film sensors occurring in the calibration tunnel. A gravity driven system was mocked up to experiment with the different volumes of water required to eliminate bubbling of the hot-film sensors, especially the volume of water in the upper reservoir tank. Any pump will tend to generate bubbles so a settling chamber is needed which would allow any air bubbles to rise to the surface of the settling chamber and separate from the working fluid. This feature is automatically provided by a gravity feed system with upper and lower reservoir tanks. The upper reservoir tank serves as a settling chamber to help separate the bubbles from the working fluid sent to the test section. The mock up tests of the gravity feed system were highly successful in preventing the formation of air bubbles on the hot-film sensors.

Control of the density profiles is required to counteract the continuous mixing which will take place in the test section. Measurements from the old water tunnel showed that mixing is approximately linear in time, and there is no period during which the density profile is stationary. These results are discussed in the appendix as part of a simple analytical model for predicting the flow rate of water needed to control the stationarity of the density profile. It is shown in the appendix that by providing a storage system for fresh water and brine that a relatively simple control system is possible. The old water tunnel did not have provision for this method of control, and it was felt that the problem of flow control should be made an integral part of the new water tunnel design.

The maximum velocity in the old water tunnel system was limited to about 45 cm/sec and the background turbulence intensity approached 10%. Some severe mechanical problems were encountered with the pump seals overheating and large vibrations were transmitted to the water tunnel structure. The new water tunnel will eliminate these difficulties by using the gravity driven system. The pressure head has already been proven capable of driving the water in the mock up to about 70 cm/sec and is

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presently only limited by the pumps which transfer the water from the lower reservoir tank to the upper tank. Plans allow for installation of a second pump to attain higher flow velocities in the future if they are found to be desirable.

3.1.2 New water tunnel design

The water tunnel with the new modifications is shown in perspective in Fig. 1. Some photographs of component parts of the water tunnel are shown in Plates 1 and 2. The structural modifications are currently near completion. The test section is 25 cm × 40 cm × 500 cm (wetted) with a 90 cm entrance section to contain large aspect ratio (50 to 1) straws used to straighten out the flow and remove large scale motions down to the size of the straw diameter. The straws will break up larger scale motions which result from numerous turns and produce a fully developed "pipe" turbulence in the straw with scales on the order of the straw diameter. If the straws were not followed by additional turbulence management techniques, the numerous jet-like flows from the straws would coalesce and generate large scale motions again. Therefore the straws will be followed by from 1 to 4 inches of open pore reticulated foam (Scott Paper Co.). The foam is available in a wide range of porosities and is impervious to degradation from salt water. The foam will serve to break up the jets exiting from the bank of straws and produce a smooth flow at the inlet to the test section. An additional function of the foam is to provide an initial mixing of the discontinuous density gradients caused by the finite number of separate return lines (in this case 10). The separate return lines are necessary to reduce the mixing during the return loop. This step structure left unmixed would persist throughout the entire length of the test section as observed in the old water tunnel. The steps would introduce a characteristic length into the flow which is probably not of scientific interest, although the design of the straw and foam section of the water tunnel does not preclude studying these kinds of problems if they are deemed useful. Since we are particularly interested in examining flows such as uniform shear, uniform density gradient problems, and wave generation from bodies, the artificial length scale must be eliminated.

The outlet manifold consists of a series of 10 weirs to provide constant back pressure on the flow in the test section. The water flows over the weir and returns to the lower reservoir tank by gravity. Water in the lower tank is pumped to the upper tank, and any excess water in the upper tank is allowed to overflow back down to the lower tank. For safety, the upper overflow drain is capable of handling the maximum pump flowrate with no flow into the tunnel test section. The upper tank contains a series of baffles which separate the pump supply line from the test section inlet line. The baffles are required to prevent any bubbles produced in the pumping operation from reaching the test section. The water is gravity fed to

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the test section through a multiturn gate valve which permits a very fine adjustment of the flowrate. A flow meter is mounted upstream of the valve. Currently we have one flow transducer (Controlotron) which must be moved from line to line during the setting of the valves. This particular flowmeter was chosen for its wide operating range and high accuracy at low flowrates. Transducers on each line which share a common flow rate computer by multiplexing would provide optimum adjustment for all ten lines. The flow runs in a 3" pipe through the valve, then to a transition section which smoothly changes from a 3" square to a 2.54 cm × 40 cm rectangle, and finally the rectangular section is turned through a radius of 6" to arrive at the entrance to the straw section.

Extra storage tanks for fresh water and brine will be necessary during a run to supply the appropriate salinity for control of the density profile with time, counteracting the continuous mixing taking place in the test section. The density of each layer will be measured at two points, at the inlet and outlet to the test section. These measurements made in each layer will supply the necessary information to adjust the rate of fresh water and brine into each layer required to hold a stationary density profile. Each of the lower reservoir tanks will have lines supplying both fresh and brine water which will be metered through solenoid valves. The solenoid valves will be duty cycled at a rate controlled by a microprocessor which will also monitor the density change in each layer. The water added to the lower reservoir tank will displace an equivalent volume of water thus maintaining the system at constant volume. The lower reservoir tanks will be maintained at constant level with an overflow line which dumps excess water out of the system. The previous water tunnel has provided us with data (see the appendix) which can be used to estimate the flow rates of fresh water and brine to each layer and the rates appear to be well within limitations on storage space and pumping rates. We expect that 3 hour runs will be possible.

3.2 Hot-film sensors

The design changes incorporated in the modified water tunnel will eliminate the gas bubble contamination problem encountered with the previous water tunnel design. Figure 2 shows a hot-film velocity signal during bubble formation and sudden separation. The bubble is rarely swept away by the flow so that the apparent loss of velocity continues to grow with time. Eliminating the small high speed propellers from the water tunnel loop and using a gravity driven system has permitted many hours of bubble-free operation in the water tunnel mock up. The bubble formation problem was one of the major reasons for modifying the water tunnel design. A need for temperature drift compensation remains however. The low overheat ratios required for operation in salt water (1.05 say) cause a relatively high sensitivity to temperature changes. This is not a major problem and

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can be solved in several ways. The simplest method may be to tape record the mean temperature change with time and correct the velocity (and density) sensors during data analysis. We expect to use this technique at first, but analog compensation of the velocity (and density) circuits may be desirable in the future.

3.3 Conductivity instrumentation

Original work has been performed to develop a new sensor and electronics for the measurement of small scale, large bandwidth conductivity (or density) fluctuations in salt water. Our earlier intention to work with the single conductivity sensor with the ground plane at infinity (see Gibson & Schwarz (1963)) has been discarded because of severe drift problems inherent in the single sensor system. It has been impossible to operate a small single sensor conductivity system drift-free for sufficient durations compatible with the long run times we seek in a continuous-flow water tunnel. Use of the single sensor approach in the water tunnel would necessitate elaborate calibration procedures to monitor the changes in the calibration. These difficulties are compounded by the nonlinearity of single sensor systems. Conductivity sensors are susceptible to drifts caused by both temperature and electrode surface changes. With a single sensor system, both temperature and surface changes at the electrode tip appear as false readings of conductivity (or density). In an effort to eliminate the surface effects, we have experimented with both 4 and 2 electrode sensors inspired by 4-wire impedance bridge techniques which eliminate lead resistance errors.

Early work with 4-wire sensors proved highly encouraging, providing good independence from drift caused by changes in the electrode surface. The 4-wire approach does have a drawback in that spatial resolution and frequency response are strongly dependent on the physical size of the sensor electrodes so it is difficult to achieve the small physical dimensions of the single sensor systems. For this reason, we have developed a 2-wire system which provides both good insensitivity to surface drift problems and allows significantly smaller physical sensing volume. An important side benefit of both the 2 and 4-wire systems is the ability to construct sensor circuits whose response is more nearly linear to changes in density. The linearity of the density measuring system permits relatively simple corrections to be made to the calibrations which change with temperature. The temperature changes in the water tunnel are slow and the temperature corrections can be easily made either electronically or digitally during data analysis.

A circuit for operating the 2-wire conductivity sensor has been developed and is currently being tested. Linearity and drift properties are shown in Fig. 3. Dynamic comparison tests are currently being performed to

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examine the spectral response of the 2-wire system against the single wire system. An experiment to compare the two sensor systems was performed in a jet of water issuing vertically upwards into an ambient field of a salt solution (more dense). The less dense jet fluid tends to rise to the surface of the container and water entrained by the jet does not contaminate the signal at the measurement position. This technique allowed sufficient experimental run times to operate separately the single and double wire sensor systems without sizeable changes in the experimental conditions. The results are shown in Fig. 4. The spectral results to date have been somewhat puzzling for the two systems appear to contain large differences, especially at frequencies below 100 Hz. The differences are disturbing and must be explained before either sensor system can be used with confidence to measure spectra and correlations in a stratified flow. The two density measuring systems should have produced nearly identical spectra, especially at the lower wavenumbers. The differences are too large to be explained by electronic circuitry alone. This was confirmed by measuring the frequency response of both the single and double wire circuits with a simulated sensor and a random white noise generator, and the results showed flat frequency response for both systems to beyond 1 kHz.

We suspect that at least part of the trouble may lie with the difficulties in calibration of the single wire sensor, which is subject to the rapid drift problem. We will attempt to reduce the drift in the single wire system in order to better compare the single and double wire systems. A second kind of test will be performed substituting temperature fluctuations for density fluctuations and a third sensor will be used to determine which conductivity sensor system is correct. A fiber film sensor with a slight overheat will be used to measure the temperature fluctuations. The two conductivity circuits will then be compared with the temperature sensor by using the known relationship between conductivity and temperature for salt water.

Bipolar conductivity electrodes are commercially available from DISA (medical instrumentation division), and will be tested to see if they are suitable as density sensors. They are relatively expensive compared to the 2-wire sensors we are able to construct but having a commercially available sensor is highly desirable. Since DISA also manufactures the hot-film velocity sensors, a future possibility would then exist for manufacture of the entire 2-velocity component and density probe - a desirable option for applications where highly trained technicians are not available to construct the relatively complicated sensor required for this type of measurement.

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4. Future Plans

4.1 Measurements

4.1.1 Flow around axisymmetric bodies

Measurements of the internal wave system generated by the body will be compared with existing theories to verify or disprove their validity. These experiments will rely heavily on flow visualization techniques (e.g., shadowgraph) as well as conductivity and hot-film probes to determine the mean and fluctuating density and velocity fields. These measurements will be concentrated on the near field of the wave system. The steady state conditions of the apparatus will allow us to make both the qualitative observations and detailed quantitative measurements relatively quickly compared with similar measurements in towing facilities.

4.1.2 Wakes of axisymmetric bodies

Observations and more detailed measurements of the wake development will be compared with the predictions of widely conflicting wake theories with the goal of determining which theory is physically reliable for useful extension to the full scale ocean problem. The generation of nonsteady internal wave motions by the turbulent wake coherent structure will be studied visually and with density and velocity measurements to assess the degree of importance of such effects for further theoretical studies.

4.1.3 Stratified shear flows

Measurements of the large scale and small scale turbulence structure, including transport of salt and momentum across the sheared region as a function of Richardson number and other properties of the flow profiles will be compared with available theoretical work, which is still rather incomplete at this time. The resulted theoretical assumptions are almost completely untested, and very few efforts are thought to correctly include the effects of interactions of the organized and random parts of the internal wave field and the remaining turbulent structure.

The experimental study of a turbulent shear flow with a linear mean profile has proven to be very fruitful in the non-stratified case (Champagne et al. 1970). In the unstratified case, there is no characteristic length scale, and in the asymptotic state far downstream of the origin of the shear layers the Taylor microscales continue to grow linearly even though the rms velocity fluctuations, Reynolds stresses, and velocity profile are constant across and along the flow. With stratification, an important physical difference is that now there is a characteristic length scale, the Richardson length, and the development of the uniform shear flow can be expected to be radically altered by stratification. With increase of turbulence

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scales, buoyancy effects become more important for the turbulence, and it may be possible to establish a true self-preserving flow in which the scales do not continue to grow as they do in the non-stratified case. The growth of the scalar fluctuation itself is of interest. Experiments in grid turbulence with a uniform, but passive, temperature gradient and no shear (Wiskind, 1962) show that the temperature fluctuations continually increase in size. The production of scalar fluctuations by the mean temperature gradient field (always positive) is considerably larger than the decay terms for scalar fluctuations. Experimental results relating the pressure-velocity correlation terms and the Reynolds stress tensor obtained in the uniform shear flow have been used as justification for modelling assumptions for these terms in theoretical calculations of stratified shear flows, e.g. Lumley and Khajeh-Nouri (1974). Neither Wiskind's measurements nor later attempts to study this type of flow have measured the crucial flux term $\overline{\rho' w'}$, the correlation between the vertical velocity and scalar fluctuation. This calls for the new instrumentation development described in the following paragraph.

A correctly formulated theoretical model must also deal with the remarkably ubiquitous ability of stratification to destroy turbulence, which apparently accounts for the strongly intermittent character of turbulence found in the ocean. Physically, turbulent mixing layers are destroyed by the stabilizing influence of gravitation on the largest scale turbulent structures. If the initial Richardson number is small, the turbulence will grow until the length scales are large enough for buoyancy to be important - then collapse will occur. Whereas field observations are made under uncontrolled and often not well enough documented conditions, careful laboratory experiments performed for a variety of well controlled and measured conditions may be able to determine the mechanism by which these intermittent processes control the overall flow structure and its evolution.

4.2 Instrumentation development

Techniques exist for the separate measurement of velocity, temperature, and density. Commercial velocity probes are readily available for the measurement of one or two components of velocity. However, there appear to be no reports in the open literature on experiments which have measured, simultaneously, velocity and density in water at a single point. Such measurements are necessary to determine the vertical energy and momentum fluxes in stratified flow.

The double-wire conductivity results will be compared with those of the single-wire probe to determine whether there are any serious operational problems in measuring dynamic signals with the two-wire conductivity sensor. We expect that when the problems are solved, the double-wire sensor will be a significant advance over the usual single-wire conductivity sensors. The

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good linearity and drift properties will make this kind of sensor highly desirable. The low drift property is probably essential for the long-term running times anticipated for the water tunnel operation. The electronic circuit required to operate the two-wire sensor is only slightly more complicated than that required for the single wire sensors and is not a serious problem. Once the double-wire sensor is operational, we will experiment with operating two or more conductivity sensors in close proximity. This is desirable for measuring coherence distances as well as the usual space-time correlations and spatial gradients.

A new probe will be developed in stages. First, a single component velocity probe will be operated in close proximity to a conductivity probe to determine if there are any serious electrical interaction effects. The conductivity probe requires a ground removed to infinity so the velocity sensor and support must be fully insulated. The two sensors must be calibrated together, and the calibration water tunnel is essential for these calibrations and test procedures. The small size of the tunnel permits a rapid change in the water concentration (density) to be made and the thermal control system provides a rapid return to the desired operating temperature. Second, the two sensors will be mounted together to obtain optimal spatial resolution. Finally, if the previous efforts prove successful, the conductivity sensor will be mounted directly on a two-component velocity sensor. Measurement of velocity and density in water appears potentially straightforward and nearly ideal. That is, the velocity and density sensors may be capable of measuring each quantity independently over sufficiently large density variations to be of interest in stratified flow. If a mixed sensitivity does result, the calibration procedure is much more difficult but can be handled by digital processing.

4.3 Facility development

There have been few attempts to build stratified, continuous flow water tunnels. The most significant problem is the change of the density and the velocity profiles with time. A control system is required to make a continuous flow stratified tunnel useful by maintaining the mean density and velocity profiles constant to permit recording sufficient data for statistical significance. A particular advantage of continuous operation over a tow tank system is the ability to use fewer probes in the experimental study. It is extremely difficult to obtain absolute calibrations for multiple probe systems often used in tow tank experiments to reduce the number of times the experiment has to be repeated to get sufficient statistical sampling. A single probe used to traverse the flow is subject to absolute error, but the relative error may be greatly reduced and permit improved data in many cases, for instance, in the measurement of velocity and density rms decay parameters.

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An ideal control system would consist of measurements of volumetric flow rates and density which would be fed to a micro computer system to determine the required changes in operating conditions. Numerous complicated interactions occur, for instance a change in density will interact to some degree with the volumetric flow rate so that in order to maintain a constant volumetric flow rate (required to hold the test section velocity constant) the flow valve opening must change accordingly. The density will be controlled by selective addition and withdrawal of the return water. The water to be added would be mixed as required from tanks of fresh water and brine by solenoid controlled valves, all monitored by the microprocessor. The control system would be not dissimilar to certain types of process control in industrial plants. Such a system could be run until some limiting condition is reached, such as the capacity of the fresh water and brine supply tanks.

At first, the system will be manually operated. Preliminary runs with several types of stratification configurations have given estimates of the mixing rate in the tunnel without external attempts to actively control the density and velocity profiles. Simple mathematical models of the tunnel, supply tanks, and mixing properties discussed in Section 3.4 incorporated in the microprocessor will provide an initial means for adjusting the flow rate of fresh water or brine to each layer.

5. Possible applications

There are a number of possible applications for which this project could supply useful experimental information. The following is a partial list of possible applications: radiation of internal wave fields from axisymmetric bodies and wakes; turbulent diffusion in stratified flows; growth and collapse of a wake in a stratified flow; dispersion of pollutants by turbulence; density currents established from outfalls; the selective withdrawal from a stratified basin. These applications would involve a number of different experimental arrangements possible within the limits of the water channel as it is presently conceived.

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References

Champagne, F. H., Harris, V. C. and Corrsin, S. 1970 Experiments on nearly homogeneous turbulent shear flow. J. Fluid Mech. $\underline{41}$, 81.

Gibson, C. H. and Schwarz, W. H. 1963 Detection of conductivity fluctuations in turbulent flow field. J. Fluid Mech. $\underline{16}$, 357.

Gibson, M. M. and Launder, B. E. 1976 On the calculation of horizontal free shear flows under gravitational influence. J. Heat Trans. $\underline{98}$c, 81.

Lumley, J. L. and Khajeh-Nouri, Bejan 1974 "Computational Modelling of Turbulent Transport," Turbulent Diffusion in Environmental Pollution. Adv. in Geophysics, vol. 18A.

Schumann, U. 1976 Realizability of Reynolds-stress turbulence models. 14th International Congress of Theoretical and Applied Mechanics, Delft, Holland.

Stuhmiller, J. H. 1976 Theoretical considerations of turbulent buoyant flow. International Seminar on Turbulent Buoyant Convection, Dubrovnik, Yugoslavia, Aug. 30-Sept. 4.

Wiskind, H. K. 1962 A uniform gradient turbulent transport experiment. J. Geophys. Res. $\underline{67}$, 3033.

UPPER RESERVOIR TANKS

LOWER RESERVOIR TANKS

OVERFLOW PIPE

PUMP AND TANK ROOM

TRANSITION SECTIONS

INLET MANIFOLD

FOAM AND STRAW SECTION

TEST SECTION
25 cm × 40 cm × 500 cm

RETURN PIPES

OUTLET MANIFOLD WITH WEIRS
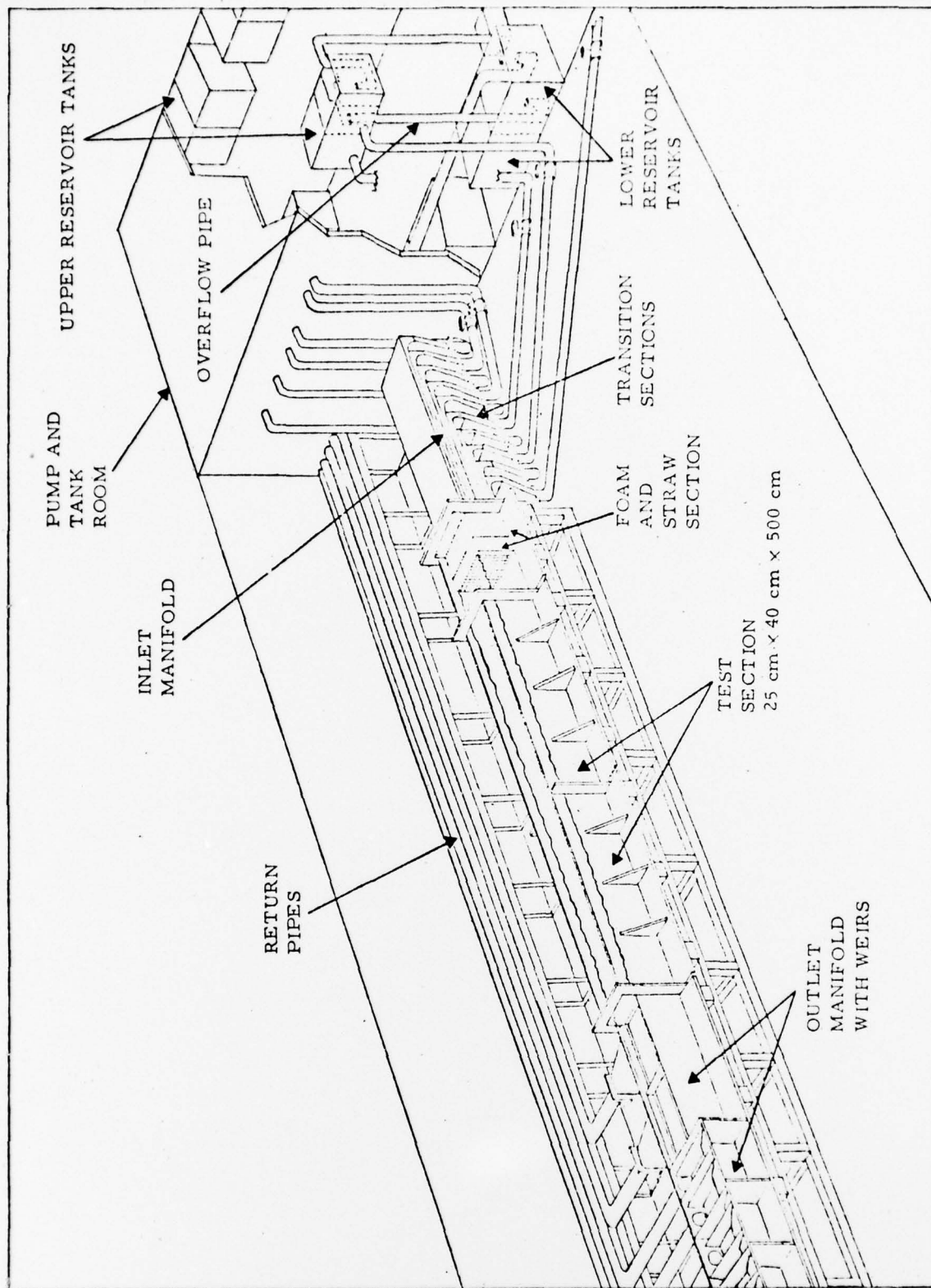
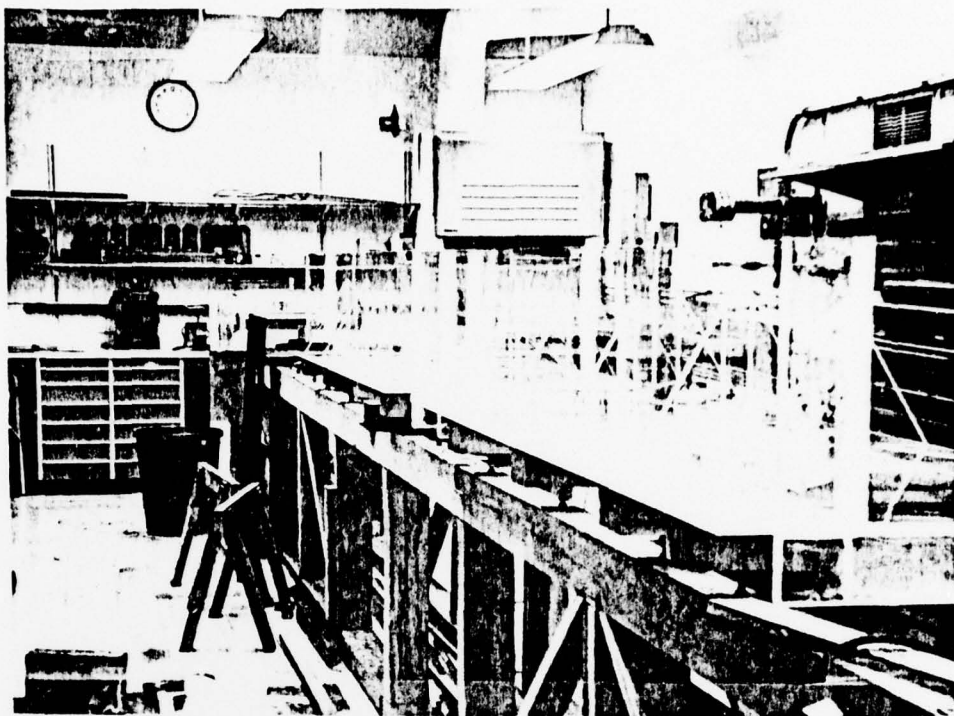Figure 1. Perspective sketch of water tunnel system.

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Plate 1(a)

Plate 1(b)

Plate 1. Photo of water tunnel components. (a) Plexiglas test section, (b) fabrication of inlet manifold.
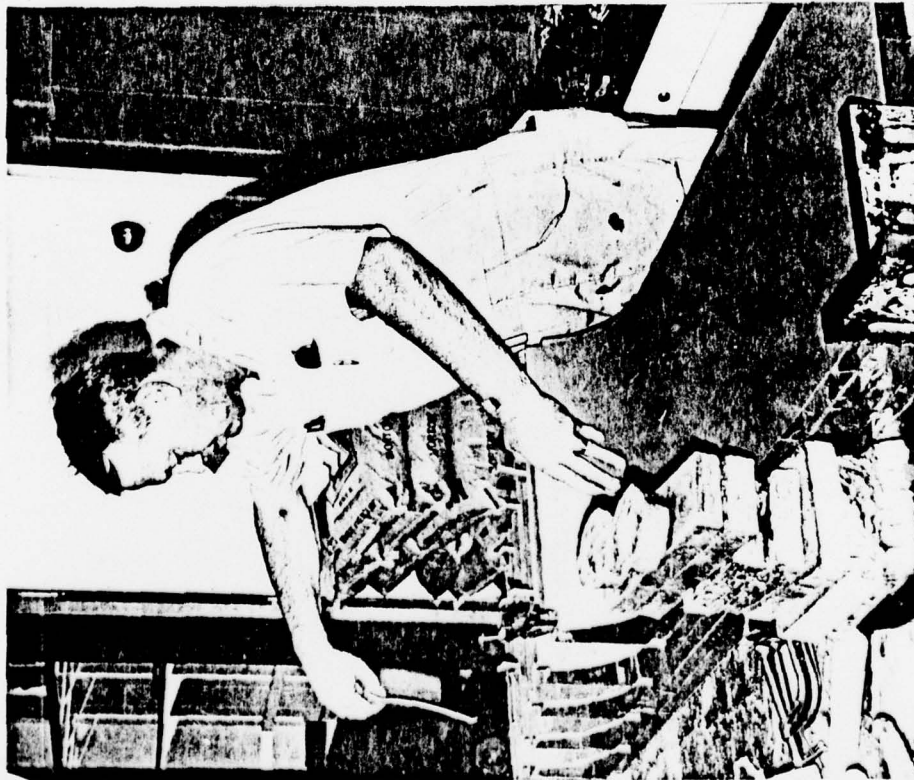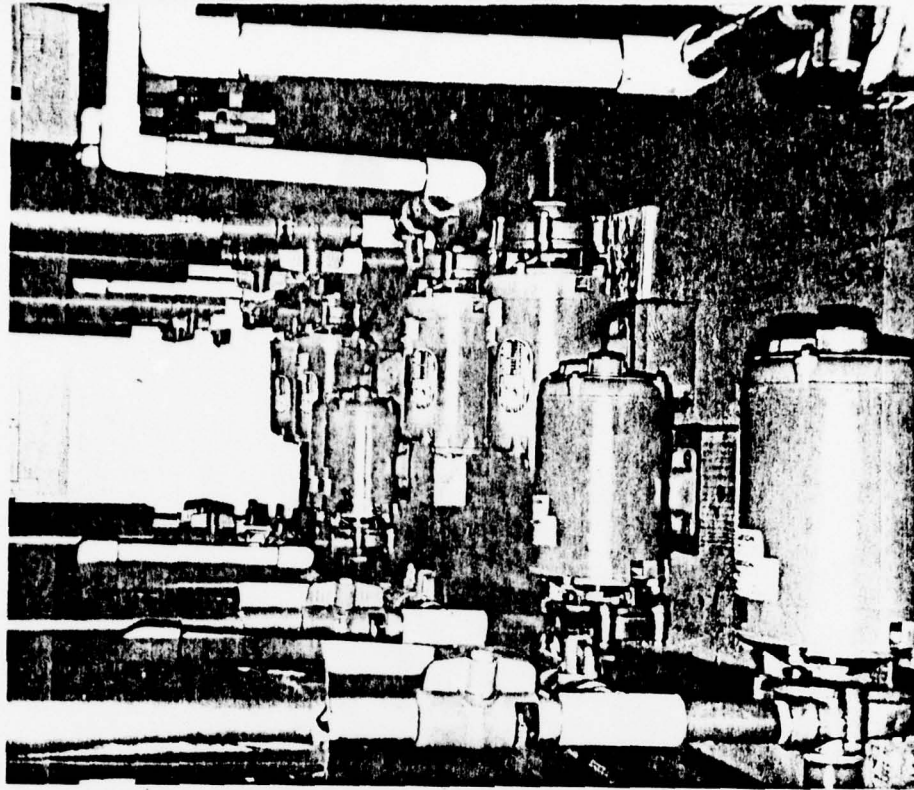
Plate 2(b)

Plate 2(a)

Plate 2.   Photo of water tunnel components.   (a) Fabrication of inlet manifold.   (b) view of centrifugal pumps in pump and tank room.

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Velocity

Temperature

Time →
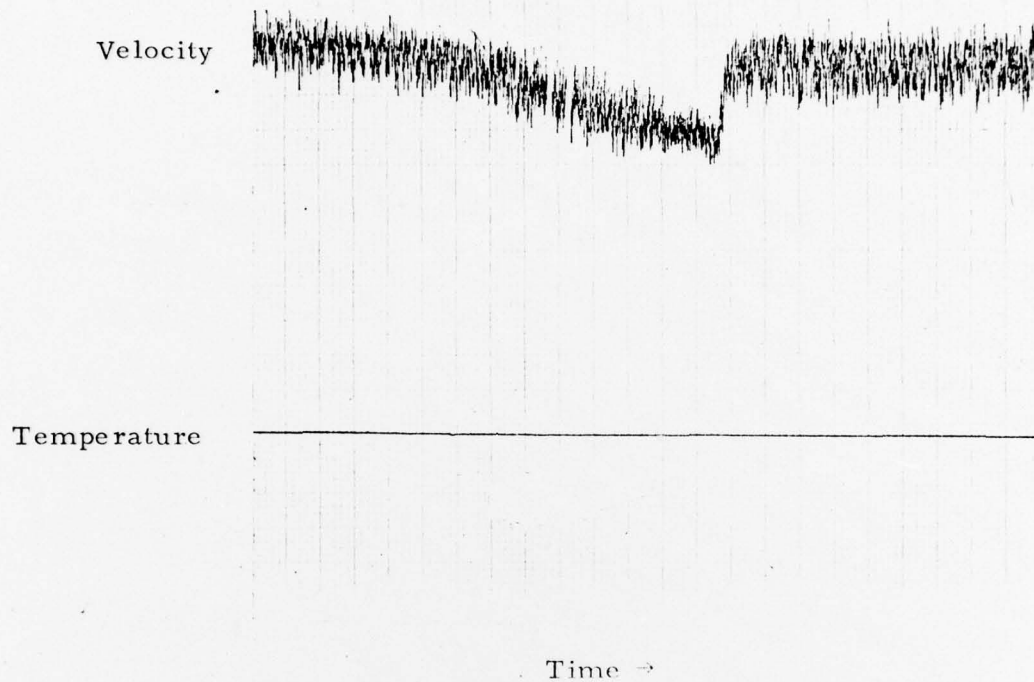
Figure 2. Velocity and temperature record. The velocity
signal shows a slow decrease as a bubble forms
on the hot-film followed by a sudden increase as
the bubble is shed. Even though the temperature
trace is nearly constant, the velocity sensor does
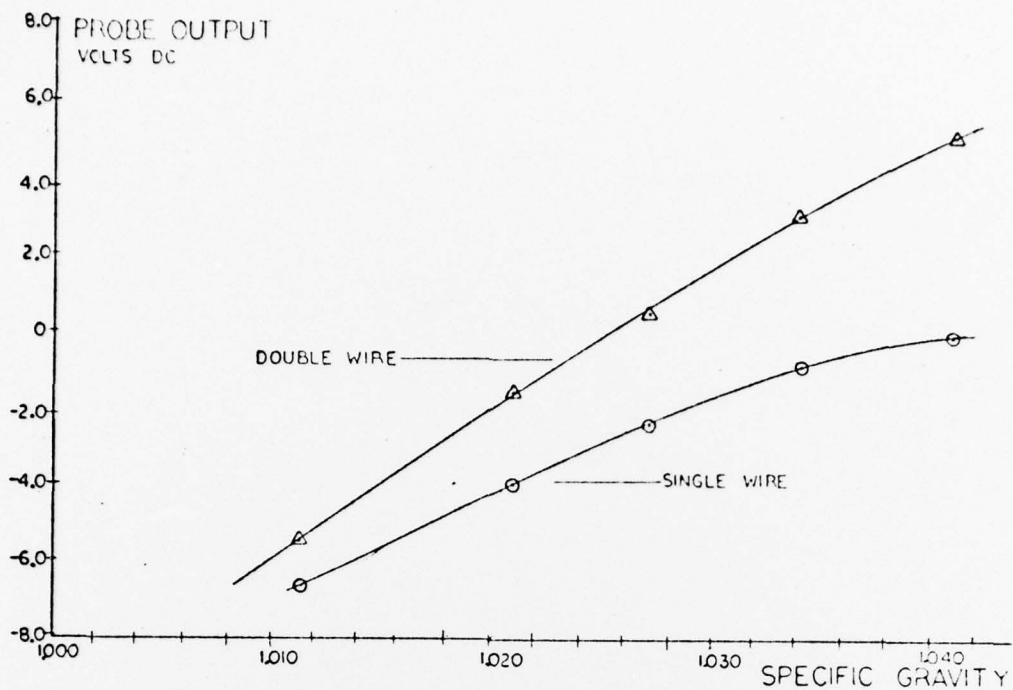not return to the original value after the bubble
was shed.

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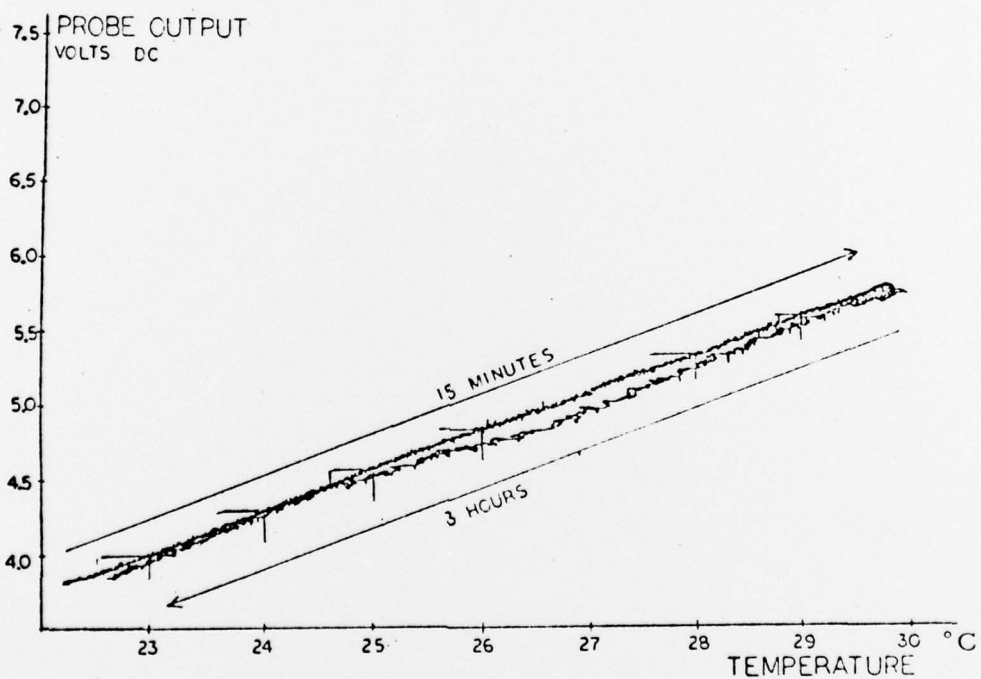
Figure 3. Some properties of the two-wire conductivity sensor.
(a) Comparison of the degree of linearity between the single
and double-wire sensors, (b) variation of the two-wire
sensor with temperature--response is linear and shows
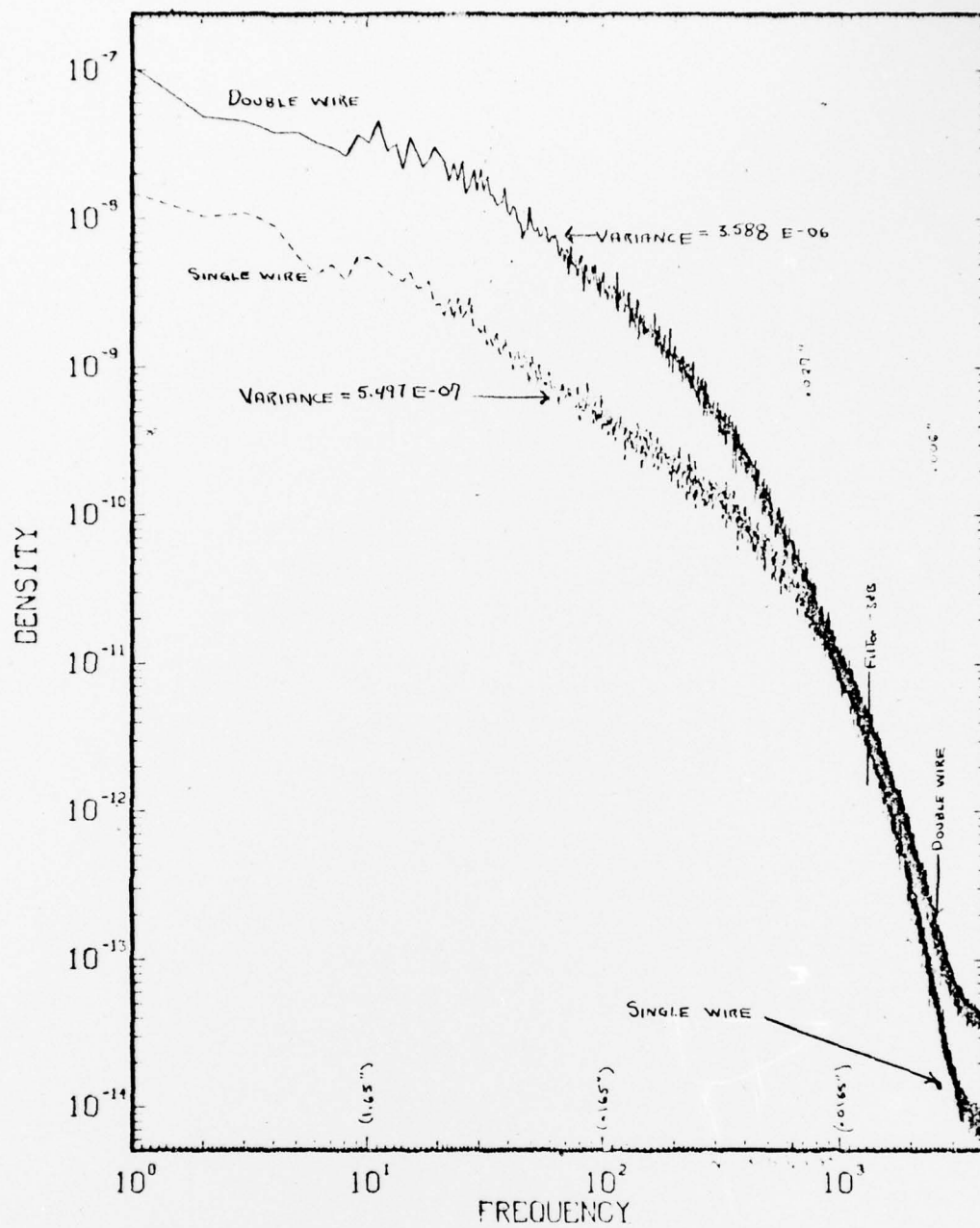negligible drift after a three hour period.

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Figure 4. Spectral comparison of single and double-wire conductivity
sensors measured in a vertical jet. $\overline{U}$ = 42 cm/sec,
X/D = 6.

APPENDIX

Steady State Mixing Model

A detailed model for the mixing within the test section requires the solution of the full Navier-Stokes equations with at least simple modeling of the important turbulence terms. This effort is clearly important, but is not yet feasible. A simpler model is required for implementation on the microprocessor, which will be used to monitor the densities of each layer and control the duty cycle of the solenoid valves which meter the flow of fresh water and brine into the water tunnel system.

The density profile will be stationary in time if the density of each layer at the test section inlet remains constant. By monitoring the incoming and outgoing densities in the lower reservoir tank and controlling the flow rates of fresh water and brine to be added to the lower tank, we should be able to hold the density profile constant at the test section inlet. A sketch of the reservoir tank with the inputs and outputs is shown in Fig. B1. We make the following assumptions: 1) the reservoir tank is well mixed, mechanical stirring may be required to achieve this in practice, 2) the added water ($\rho = \rho_a$) is either all fresh ($\rho_a = \rho_f = 1.0$ g/cm^3) or all brine ($\rho_a = \rho_s = 1.2$ g/cm^3) depending on whether or not the tank density (which is also the density at the test section inlet, ρ_i) is above or below the desired density, 3) the water tunnel system operates at constant volume.

1

These assumptions result in the following set of equations:

Mass conservation . . . . $\rho_o Q_o + \rho_a Q_a = \rho_i Q_d + \rho_i Q_i$ (B1)

Volume conservation . . . $Q_o + Q_a = Q_d + Q_i$ (B2)

Constant velocity . . . . $Q_o = Q_i$ (B3)
(volumetric flowrate)
in any layer

Note that this system of equations applies to either the case where the density is too low and salty water must be added or where the density is too high and fresh water is required. Solving Eqns B1 - B3 for the ratio of the flowrate to be added to the flowrate of water in the layer Q_a/Q_i gives

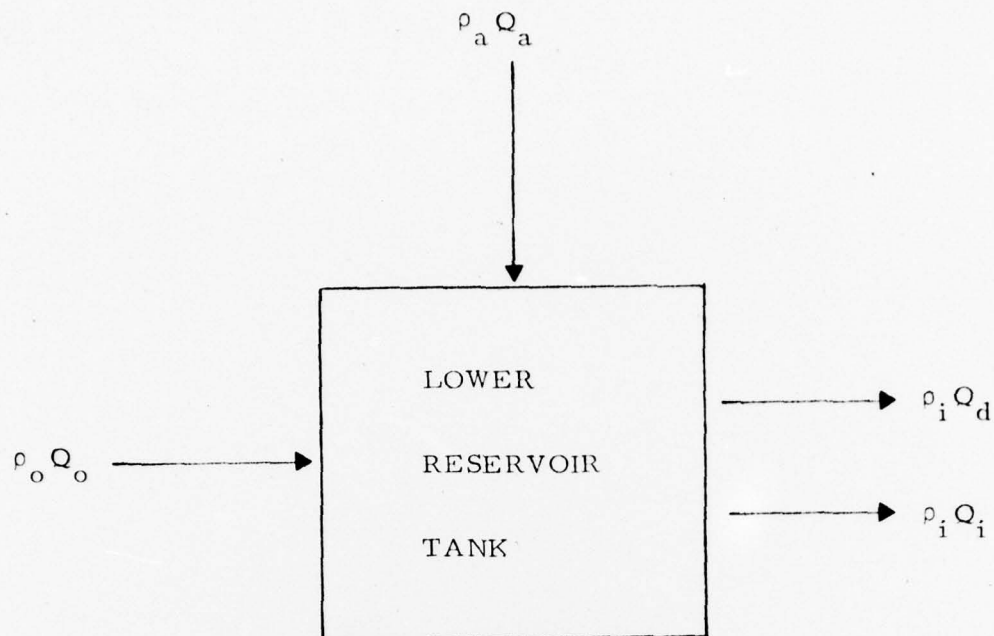$$\frac{Q_a}{Q_i} = \frac{\Delta\rho/\rho_k}{1 - \rho_a/\rho_i}$$ (B4)

where $\Delta\rho = \rho_o - \rho_i$ is a quantity which is measured by two density sensors at the appropriate places in the water tunnel system. Depending on whether the added water is fresh or salty, the ratio of the flowrates Q_a/Q_i may have greatly different magnitudes. The results for Q_f/Q_i are shown in Fig. B2 and those for Q_s/Q_i are shown in Fig. B3. The family of curves in each figure represents various values of the mixing parameter $\Delta\rho/\rho_i$. The curves for both Fig. B1 and Fig. B2 would be more nearly alike if we were to operate the tunnel about a mean density of 1.1 g/cm^3, but this may not be desirable since the slightest evaporation occurring when the water density approaches the saturated density of 1.2 g/cm^3 can cause a rapid build up of solid salt particles which will tend to clog the straw and foam

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turbulence reduction elements. For this reason, we expect to operate most experiments close to the fresh water condition. Thus when the density at the test section inlet ρ_i is too low and salty water must be added to this layer, then Fig. B3 shows that the relative flowrate of salt (say at $\rho_i = 1.03$, $\Delta\rho/\rho_i = -0.01$) is $Q_s/Q_i = 0.06$, but when the density is too high by the same amount ($\Delta\rho/\rho_i = +0.01$), the flowrate of fresh water is $Q_f/Q_i = 0.34$. The flowrate of fresh water required is much larger than the flowrate for salt water assuming the same magnitude deviation from a desired density. This requires a capacity for much larger storage reservoirs of fresh water compared to those required for salt water.

Figures B2 and B3 may be used to estimate the flowrates of fresh water and brine which would have been required to hold the density profile stationary in the old water tunnel and thereby aid in the design of the control system for the new water tunnel. An experiment was run in the old water tunnel using a biplane grid of lucite rods with a mesh length of 2" to destroy the discrete layering at the inlet to the test section. The mean speed of all 12 layers was approximately 16 cm/sec (uniform velocity profile) and the uniform density gradient $\partial\rho/\partial z$ was -0.00183 g/cm^4 (Brunt-Viassala frequency, $N = 1.34$ sec^{-1}). The density of each layer as a function of time is shown in Fig. B4. We can estimate the maximum mixing rate by using the slope of layer 1 from Fig. B4, say,

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$\partial\rho/\partial t \sim -1.38 \times 10^{-4}$ g-cm^{-3}-min^{-1} and at 16 cm-sec^{-1} and a test section length of 610 cm. $\Delta\rho/\rho_k \approx -10^{-4}$. The volumetric flowrate of each layer was about 40 gals/min (Q_i) so that for a density mixing parameter $\Delta\rho/\rho_i = -10^{-4}$, $Q_s/Q_i = 7 \times 10^{-4}$ from Eqn B4 giving a salt flowrate of about 0.03 gal/min. Thus a 100 gal reservoir tank of salt water would last about 11 hours assuming that 5 layers required this maximum flowrate. However, if we consider the rate of mixing in layer 11, $\partial\rho/\partial t \approx +1.38 \times 10^{-4}$ gm-cm^{-3}-min^{-1} and a mixing parameter of $\Delta\rho/\rho_i = +10^{-4}$, then the flowrate of fresh water required is $Q_f/Q_i = 0.01$ from Eqn B4 giving a fresh water flowrate of about 0.3 gal/min. Assuming 5 layers require this flowrate of fresh water to maintain constant density, a storage reservoir of 300 gals would last 3.3 hours. The storage reservoir for fresh water could be doubled or tripled, but clearly the limiting factor on the stationary running times is the amount of fresh water which can be stored. These estimates are probably somewhat conservative, but they serve to illustrate some of the limitations on the control of a continuous flow stratified water tunnel.

4

$$\rho_a Q_a$$

```
                    ┌─────────────────┐
                    │                 │
                    │   LOWER         │ ──────────▶  ρ_i Q_d
                    │                 │
  ρ_o Q_o  ───────▶ │   RESERVOIR     │
                    │                 │ ──────────▶  ρ_i Q_i
                    │   TANK          │
                    │                 │
                    └─────────────────┘
```

where ρ = density

Q = volumetric flow rate

and the subscripts denote:

    i = input to the test section

    o = output from the test section

    d = discharge out of the water tunnel system

    a = water added to system; either f for fresh water,
         or s for salt water (brine)

Figure B1. Diagram of lower reservoir tank indicating the various
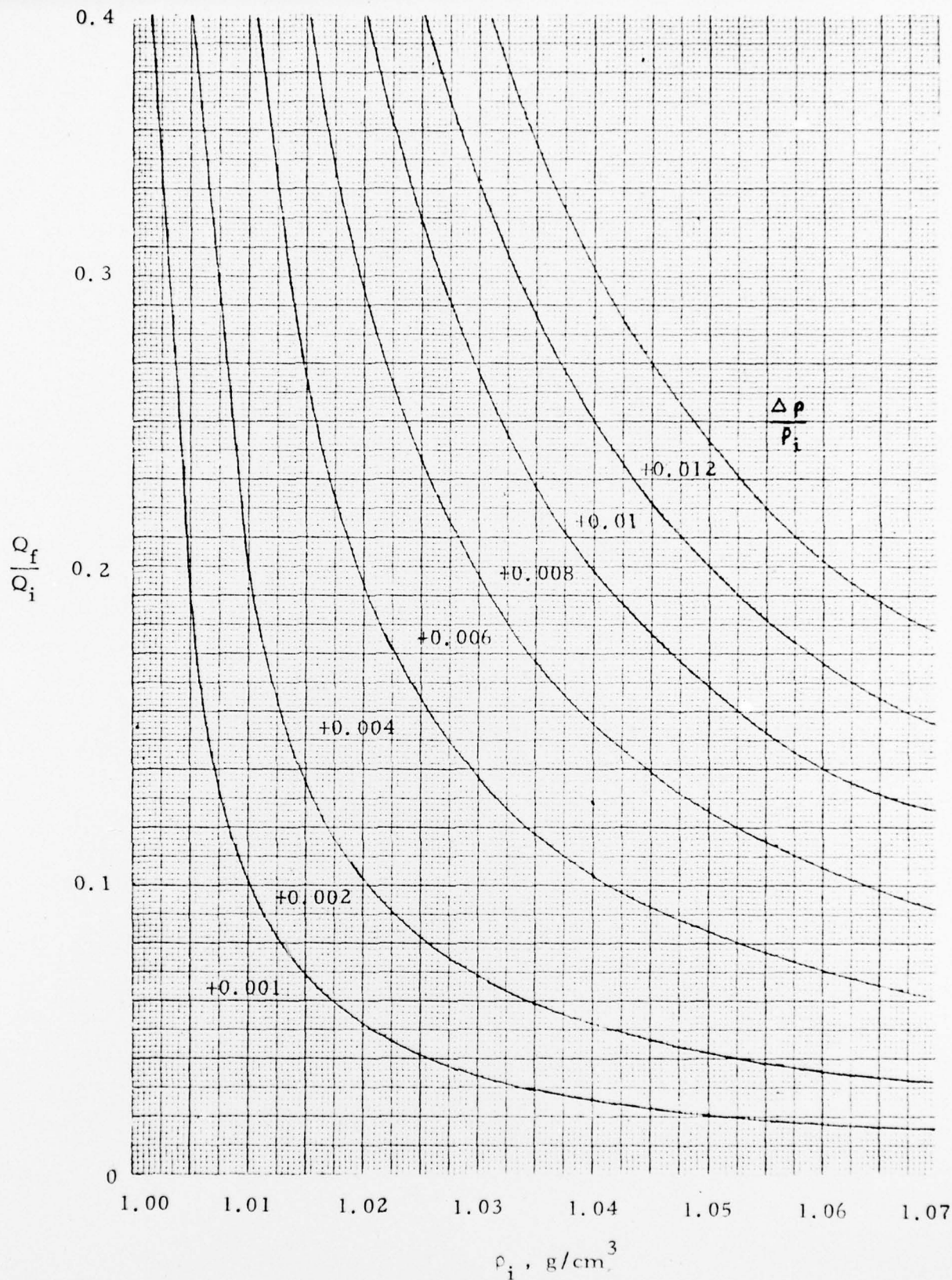flows into and out of the system.

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Figure B2. Fresh water flowrate required to reduce the density gained by mixing to the desired test section inlet density ρ_i.
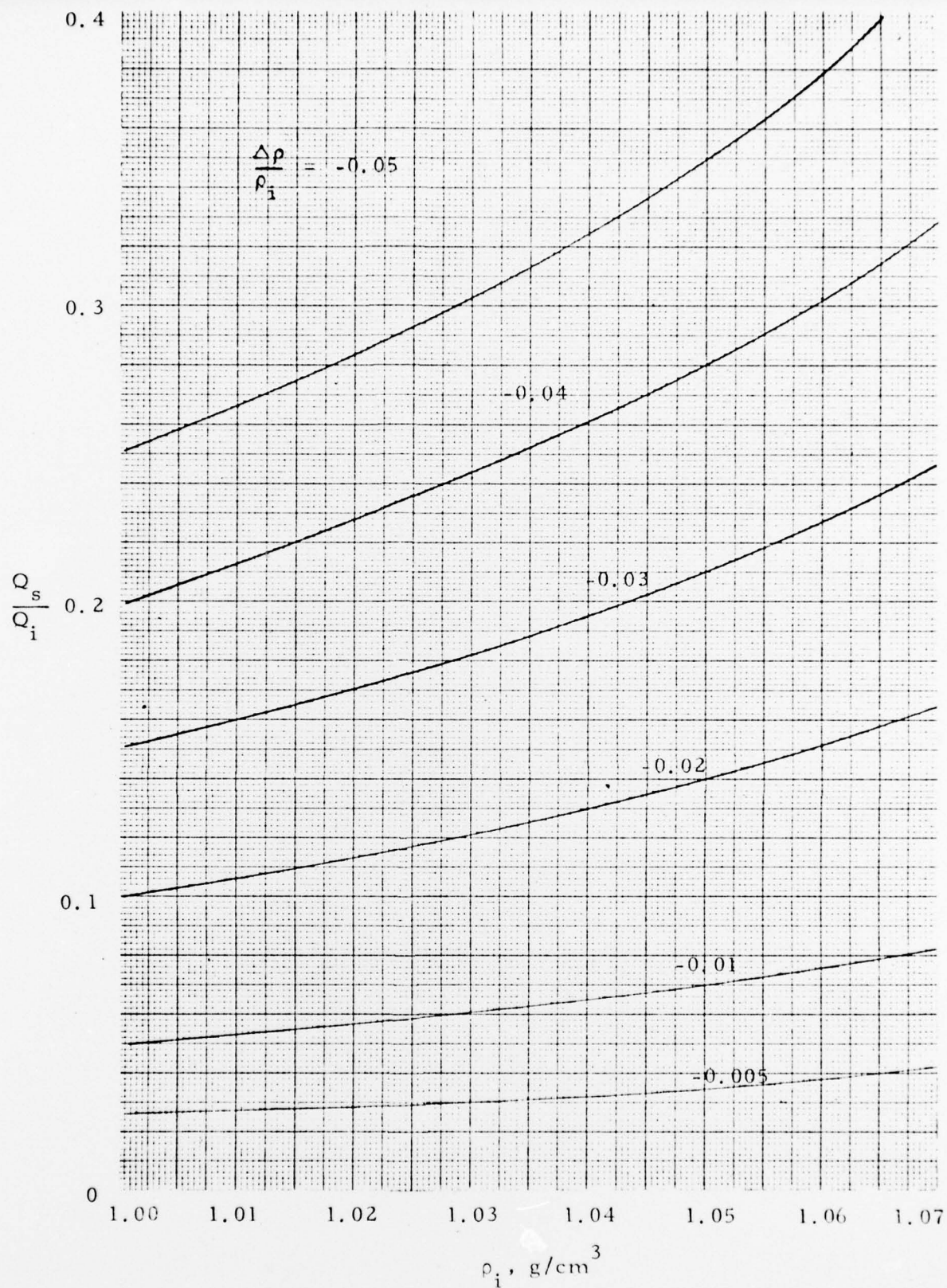
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Figure B3. Salt water flowrate required to increase the density lost by mixing to the desired test section input density ρ_i.
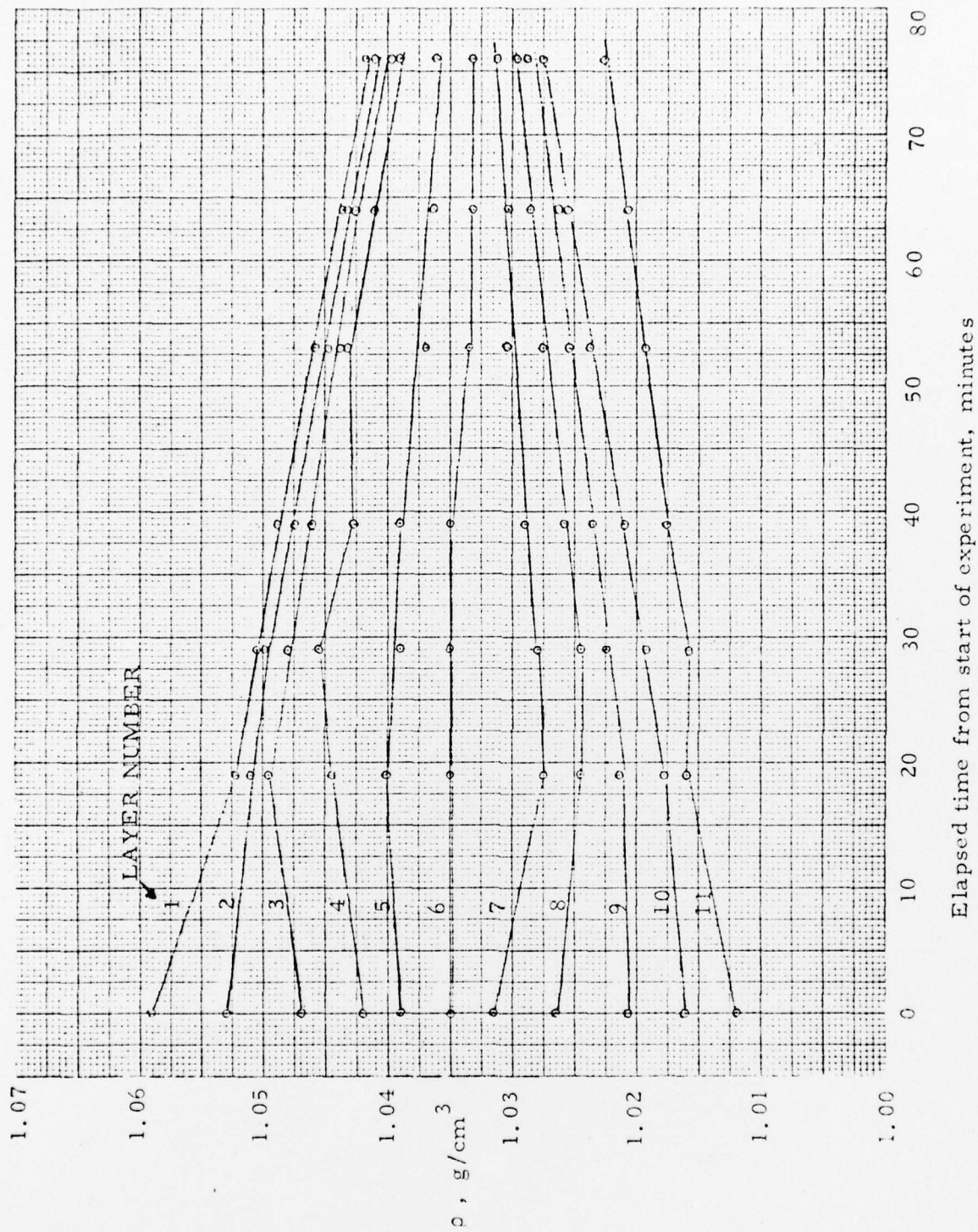
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Figure B4. Typical density history for each layer of a stratified grid turbulence experiment. The mean speed is 16 cm/sec, grid mesh is 5.08 cm, and no attempt was made to hold the density stationary.

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